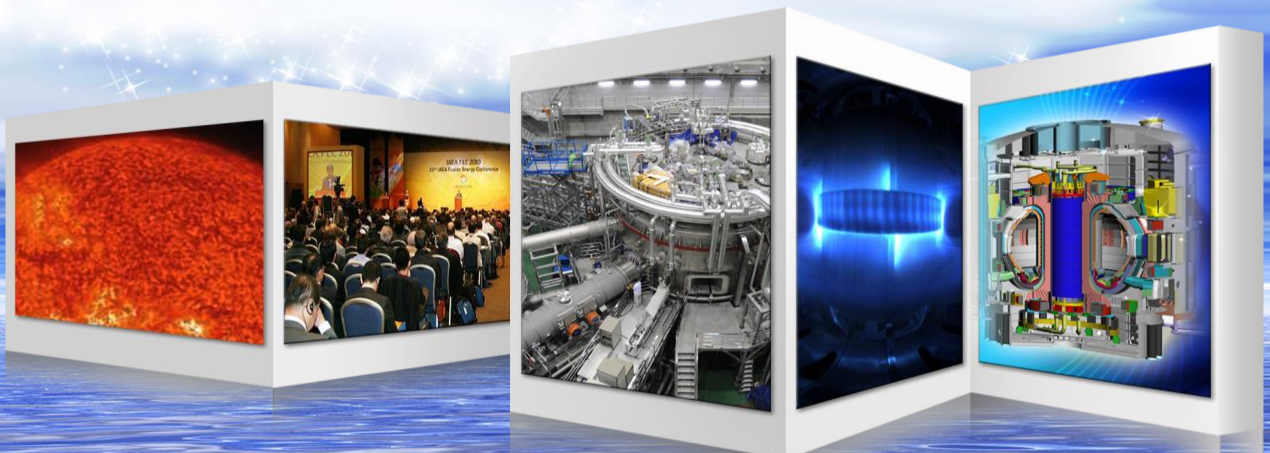
Introduction of Korean Fusion Program : KSTAR, ITER and K-DEMO



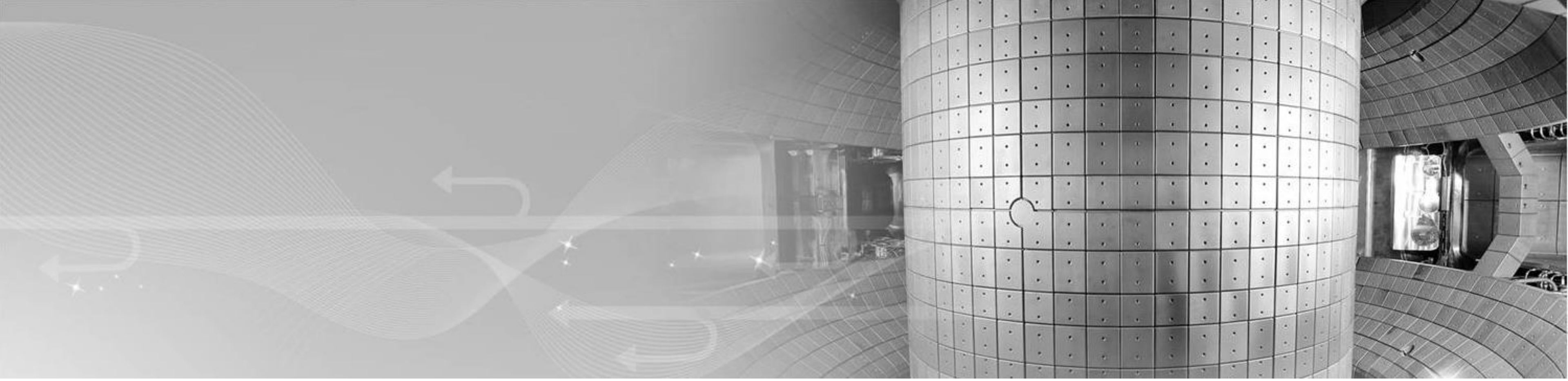
Si-Woo Yoon
National Fusion Research Institute, Daejeon, Korea

Global Research Platform Workshop 2019
Atkinson Hall, San Diego, 17-18 SEP 2019

Ministry of Science and ICT

nst National Research Council of Science & Technology

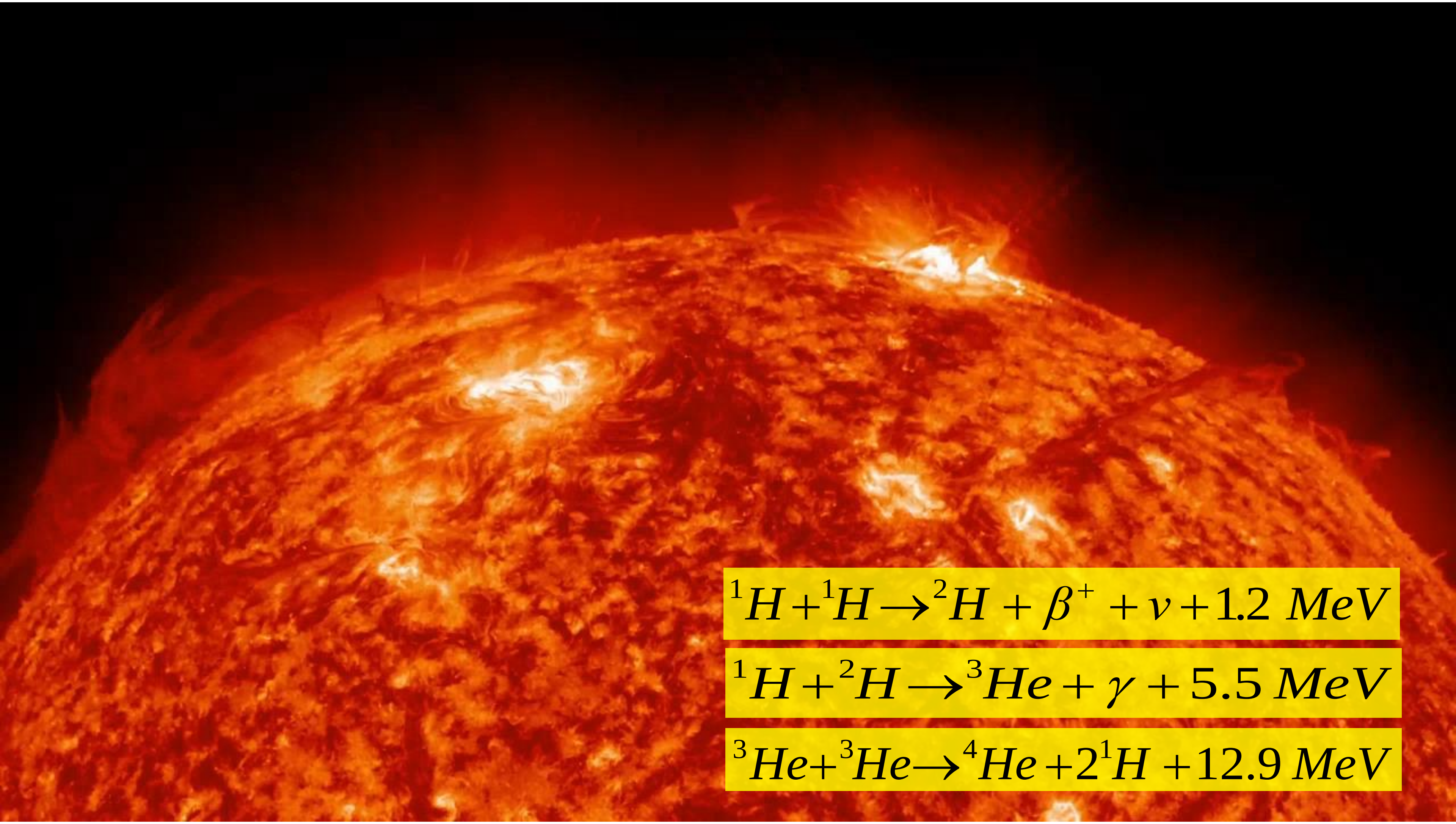
NFRI National Fusion Research Institute



Contents

- Introduction to KSTAR program
  (application of vacuum tubes to KSTAR)
- Introduction to ITER project
- Strategy for DEMO (V-DEMO and Fusion Loadmap)

Overview of Fusion R&D - Fusion Energy



$$^{1}H + {}^{1}H \rightarrow {}^{2}H + \beta^{+} + \nu + 1.2\ MeV$$

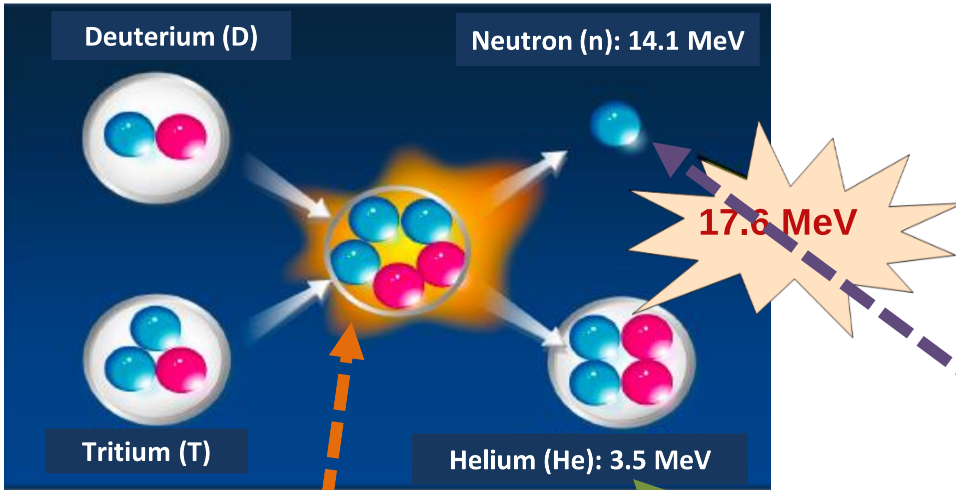
$$^{1}H + {}^{2}H \rightarrow {}^{3}He + \gamma + 5.5\ MeV$$

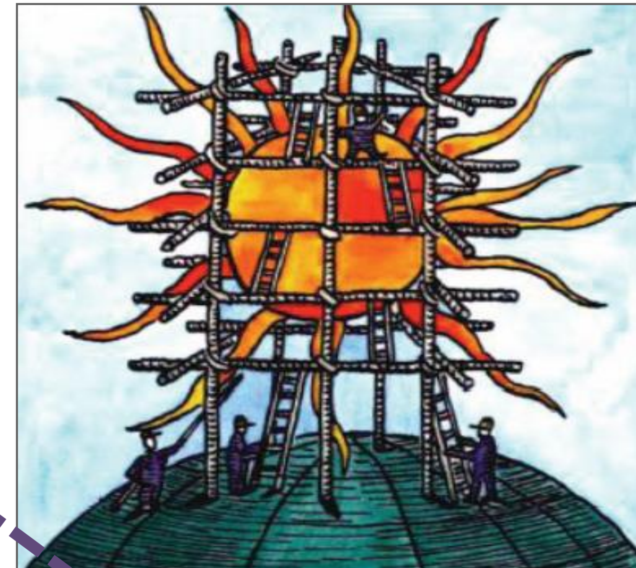
$$^{3}He + {}^{3}He \rightarrow {}^{4}He + 2\,{}^{1}H + 12.9\ MeV$$

- Fusion energy (nuclear fusion) .. The source of energy that the sun and stars emit for 10 billion years
- The most natural and universal energy source - Steady, Unlimited, and Natural Energy

Overview of Fusion R&D – Realization of Artificial Sun on Earth

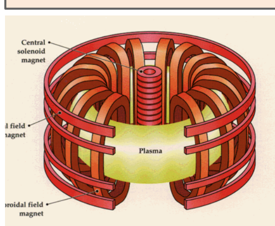
- **Representative fusion reaction**

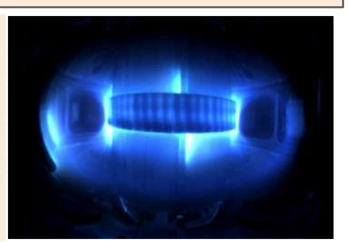


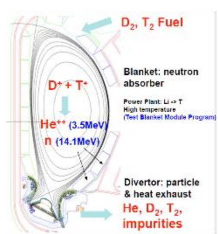


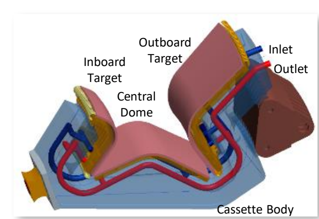
- **Essential tasks for commercialization of nuclear fusion**

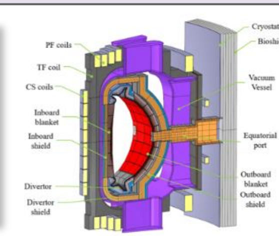
1. High-temperature plasma containment	2. Fusion thermal output	3. Extreme materials and power conversion
: High-performance plasma heating : Long-time operation control : KSTAR Core Technology Research	: D-T fusion reaction : α -particle (^4He) confinement : ITER Core Technology Research	: Neutron energy conversion (blanket) : Self sufficiency of tritium fuel : DEMO Core Technology Research







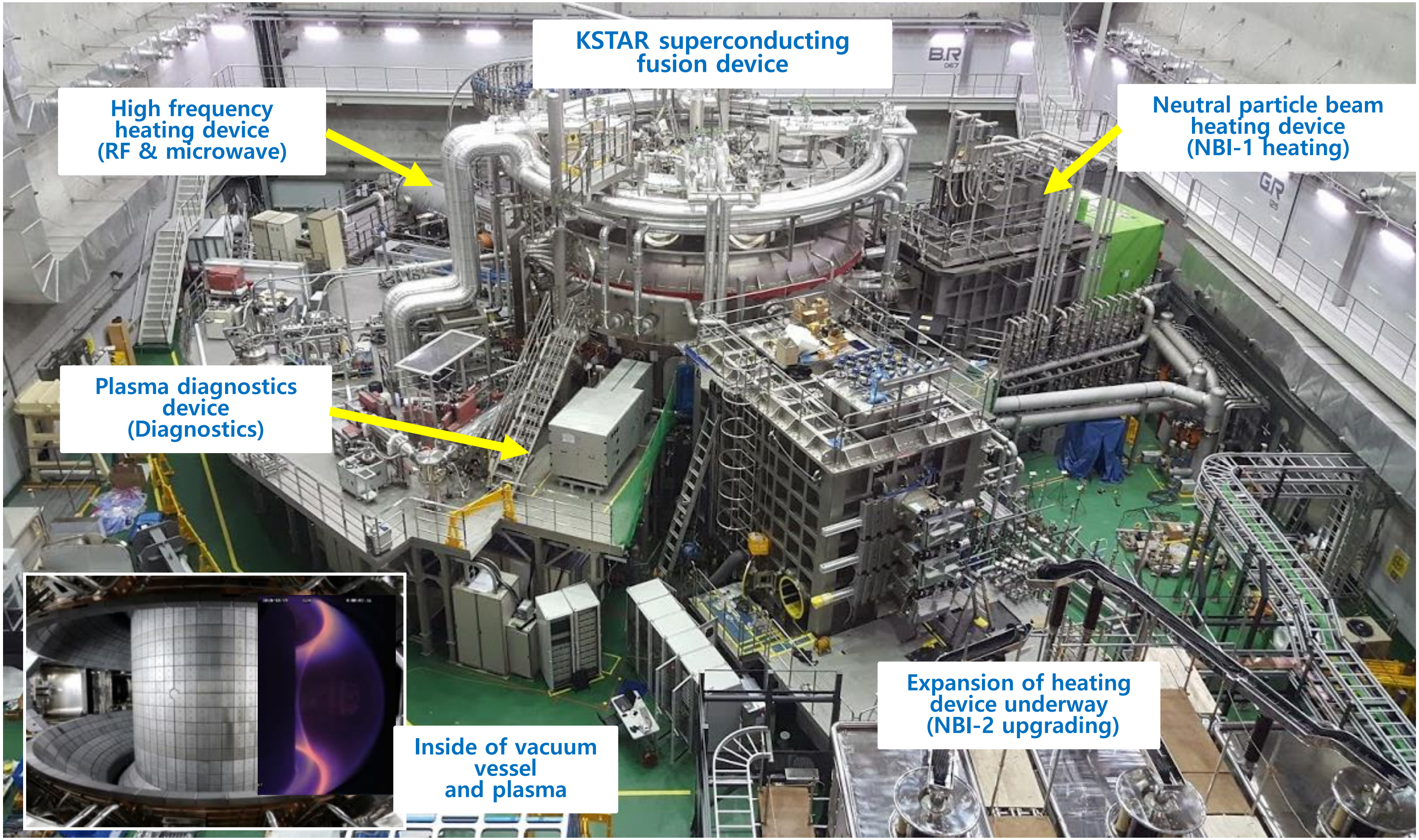




3a. KSTAR (Korea Superconducting Tokamak Advanced Research)

Vision

- Secure the technology for construction and operation of superconducting fusion device
- Lead the research for long-time operation of high-performance plasma and secure the core technology for fusion reactor



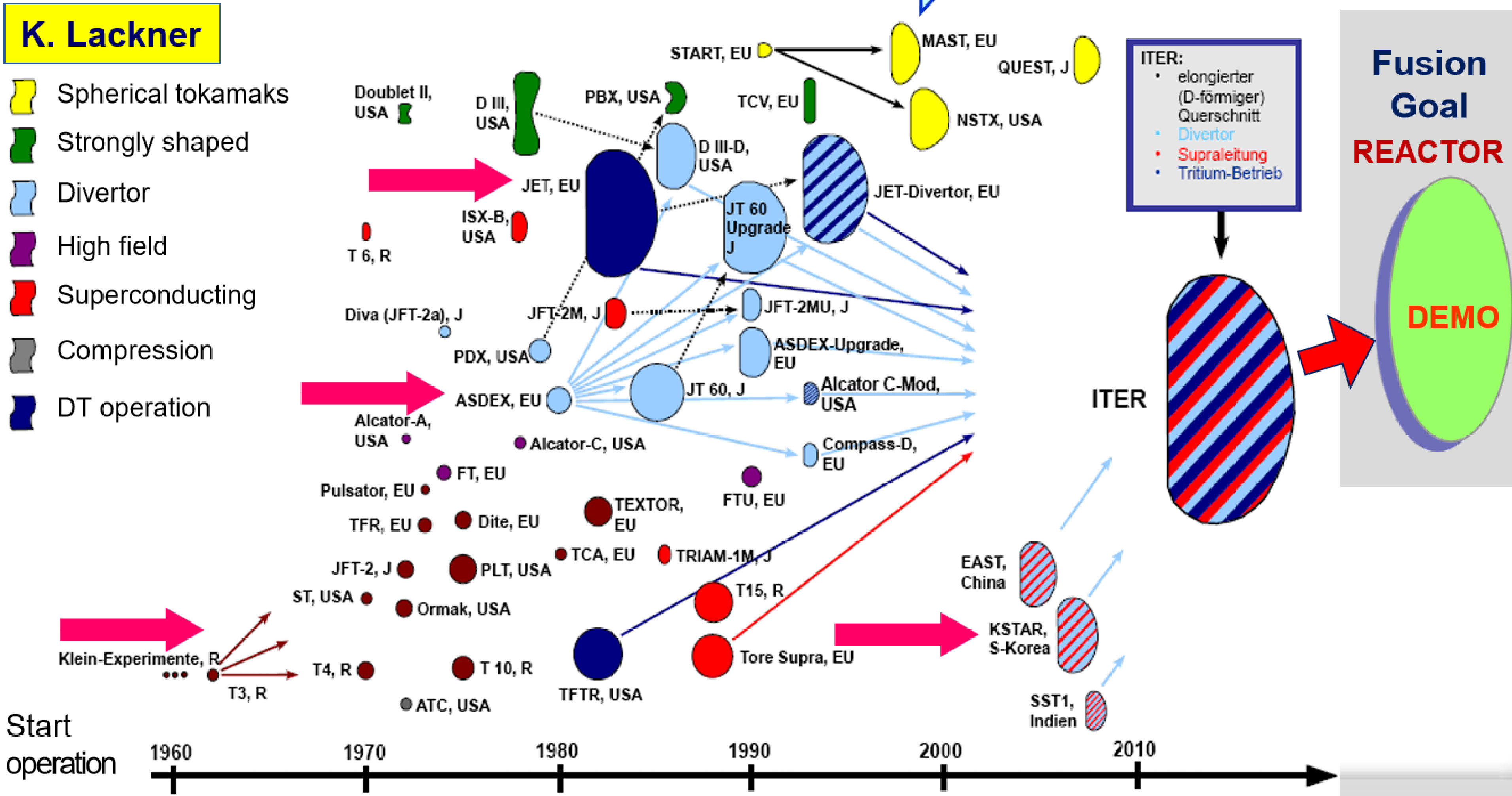
World-wide Fusion Research Program

◆ 20th Century: US-EU-RF-JA lead fusion studies;

As a result, the fusion research reached on the final demonstration to assess the scientific and technological feasibility of fusion energy realization.

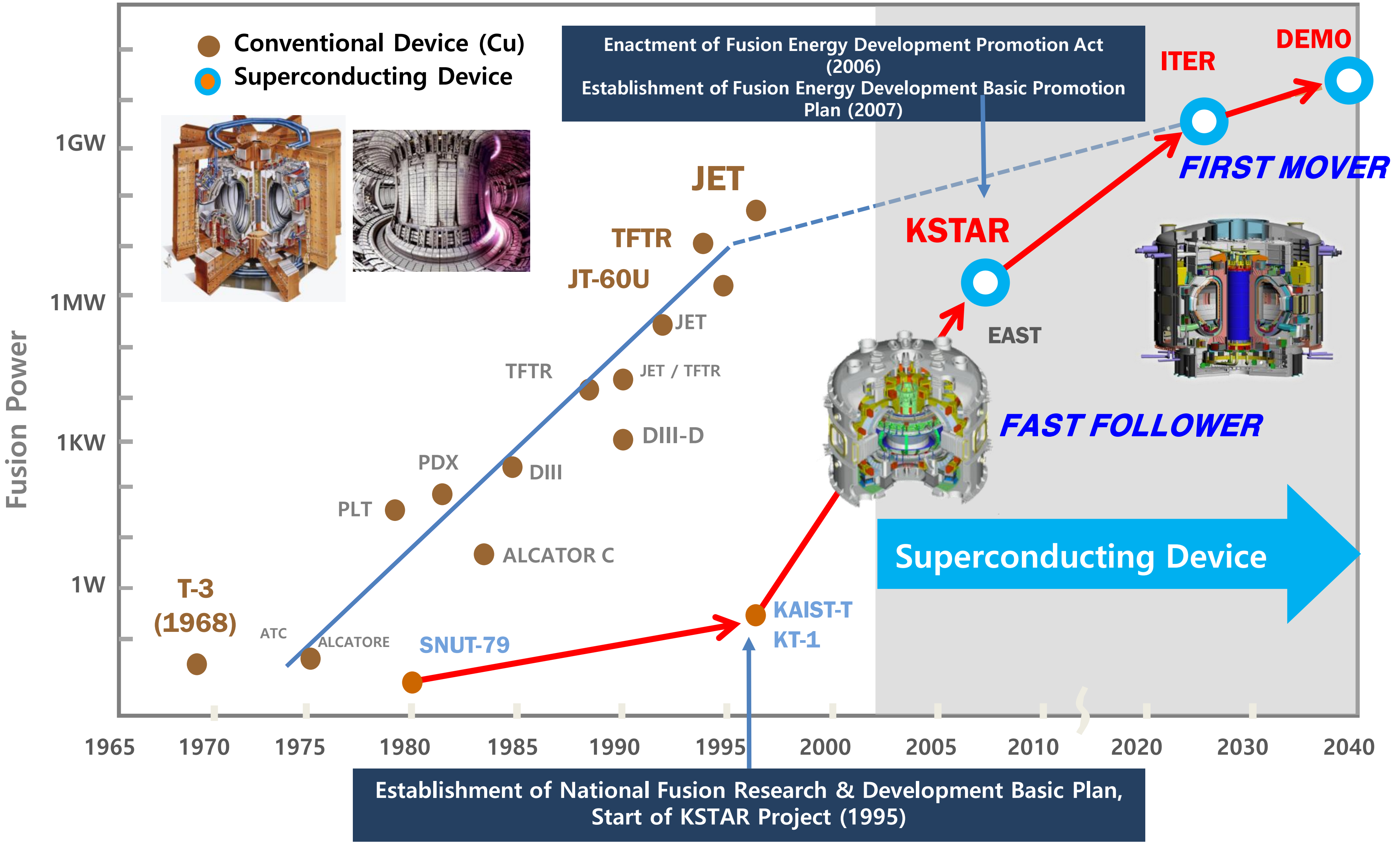
ITER Project:

International research project in participation of world leading scientists & engineers



Overview of Fusion R&D - Global Fusion Trends and Korea's Mid-Entry Strategy

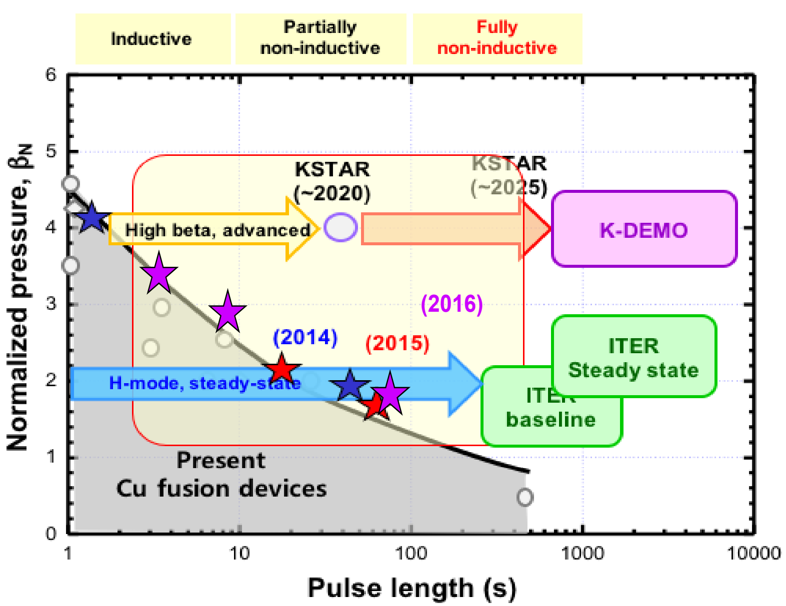
- **Changes in fusion paradigm:**
  - Pulse type → Long-time operation using superconducting magnet
  - West-centered (US, Europe) → Asia-centered (Korea, China, Japan)



KSTAR mission is *to explore the steady-state operation at high performance*

Operation goals

- to achieve **steady state H-mode** operation with resolving **engineering issues (ELM, disruption)** and
- to explore **high performance** operation modes with resolving **harmful MHDs**



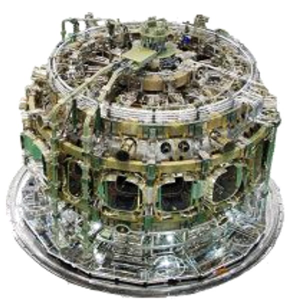
Key parameters of KSTAR, ITER & K-DEMO

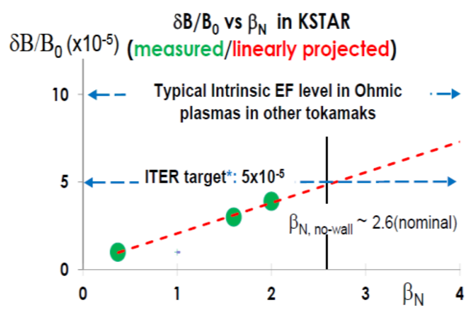
Parameters	KSTAR (achieved)	ITER (Baseline)	K-DEMO (Option II)
Major radius, R_0 [m]	1.8 (←)	6.2	6.8
Minor radius, a [m]	0.5 (←)	2.0	2.1
Elongation, κ	2.0 (2.16)	1.7	1.8
Triangularity, δ	0.8 (←)	0.33	0.63
Plasma shape	DN, SN	SN	DN (SN)
Plasma current, I_P [MA]	**2.0 (1.0)**	15	> 12
Toroidal field, B_0 [T]	**3.5** (←)	5.3	7.4
H-mode duration [sec]	**300 (70)**	**400**	**SS**
β_N	**5.0 (4.3)**	**~ 2.0**	**~ 4.2**
Bootstrap current, f_{bs}	**(~0.5)**		**~ 0.6**
Superconductor	Nb_3Sn, NbTi	Nb_3Sn, NbTi	Nb_3Sn, NbTi
Heating /CD [MW]	**~ 28 (10)**	~ 73	120
PFC	C, W	W	W
Fusion power, P_{th} [GW]		~0.5	~ 3.0

How can KSTAR support ITER?
Exclusive uniqueness in KSTAR could make it.

▶ Better plasma symmetry

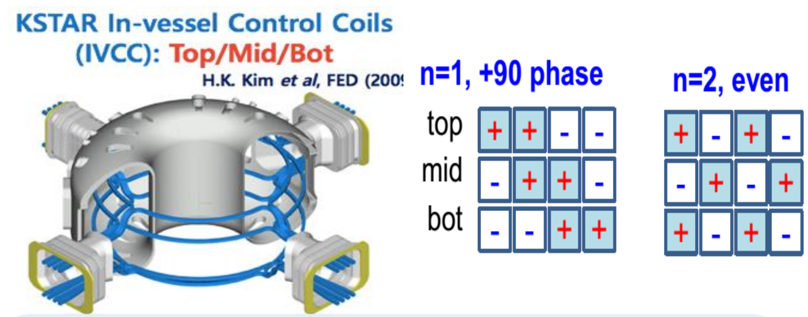
- Lowest error field ($\delta B/B_0$~$1x10^{-5}$)
- Lowest toroidal ripple (~0.05 %)





▶ Better instability control with IVCC

- Uniquely top/middle/bottom coils
- Reliable ELM-crash suppression (>30s)



▶ Better understanding by Advanced diagnostic

- Profile and 2D imaging diagnostics
- Physics validation of MHD & confinement

ECEI

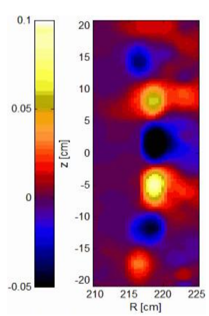
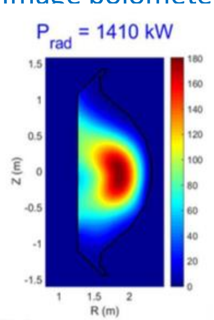
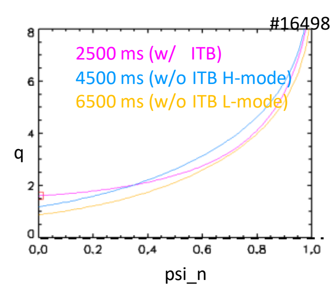


Image bolometer

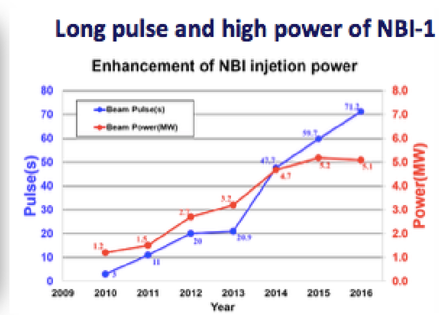


MSE

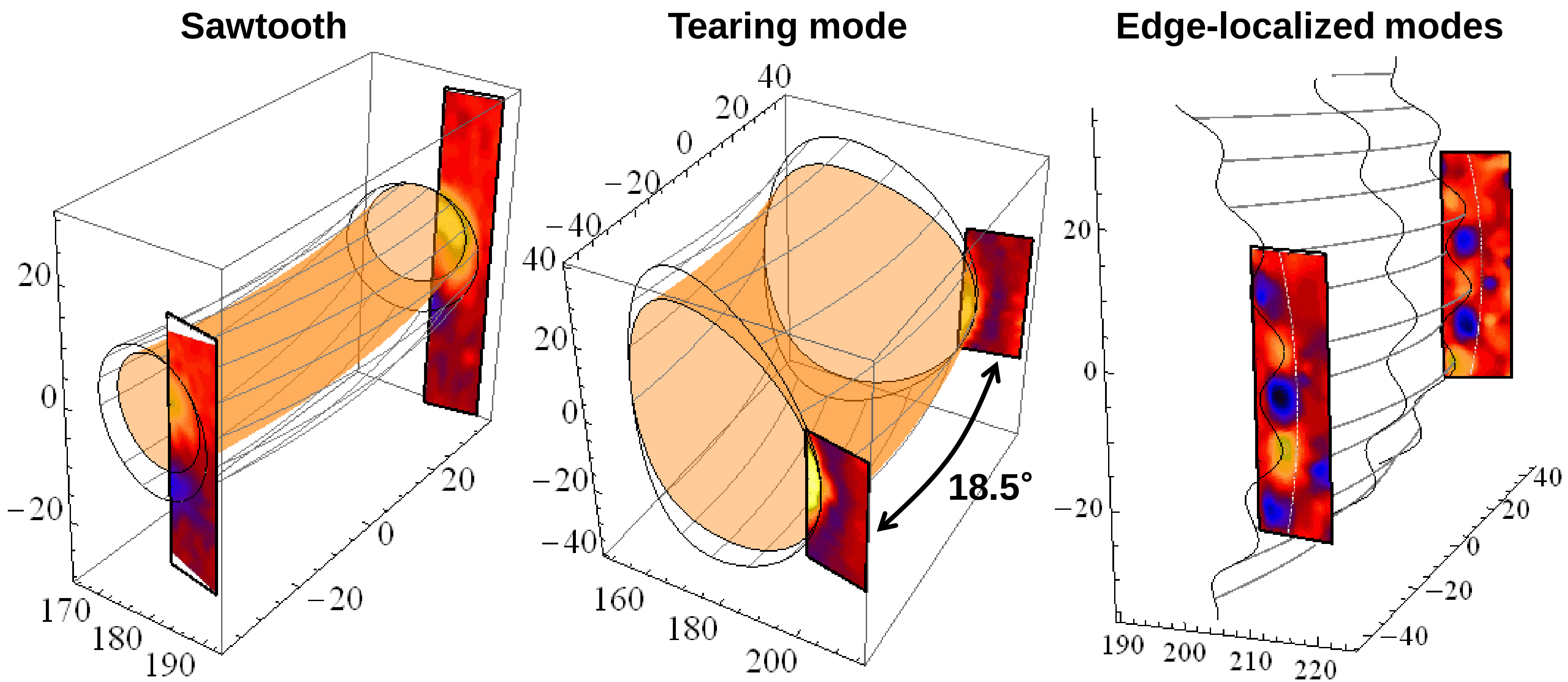


▶ Better efficiency in heating/CD & ready to upgrade

- Long pulse high beta op. using NBI (>70s)
- 2nd NBI system is under construction



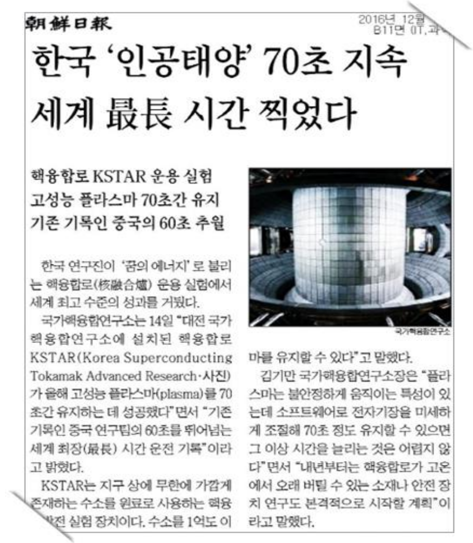
3D Imaging of MHD Instabilities



- Two independent ECEI systems will be installed on the KSTAR in 2018, which is toroidally separated by 18.5 degree, to visualize the MHD and turbulence in quasi-3D for wide range of KSTAR operation.
- Due to flexible optics and LO system, the view position of two ECEIs will be focused anywhere in the midplane with sufficient vertical coverage.

KSTAR Project - World's Top Research Achievement

- Secured the core technology for fusion reactor as world leader for long-time operation of fusion plasma


朝鮮日報
2016년 12월 B11면 0T.과

한국 '인공태양' 70초 지속 세계 最長 시간 찍었다

핵융합로 KSTAR 운용 실험
고성능 플라스마 70초간 유지
기존 기록인 중국의 60초 추월

한국 연구진이 '꿈의 에너지'로 불리는 핵융합로(核融合爐) 운용 실험에서 세계 최고 수준의 성과를 거뒀다.

국가핵융합연구소는 14일 "대전 국가핵융합연구소에 설치된 핵융합로 KSTAR(Korea Superconducting Tokamak Advanced Research·사진)가 올해 고성능 플라스마(plasma)를 70초간 유지하는 데 성공했다"면서 "기존 기록인 중국 연구팀의 60초를 뛰어넘는 세계 최장(最長) 시간 운전 기록"이라고 밝혔다.

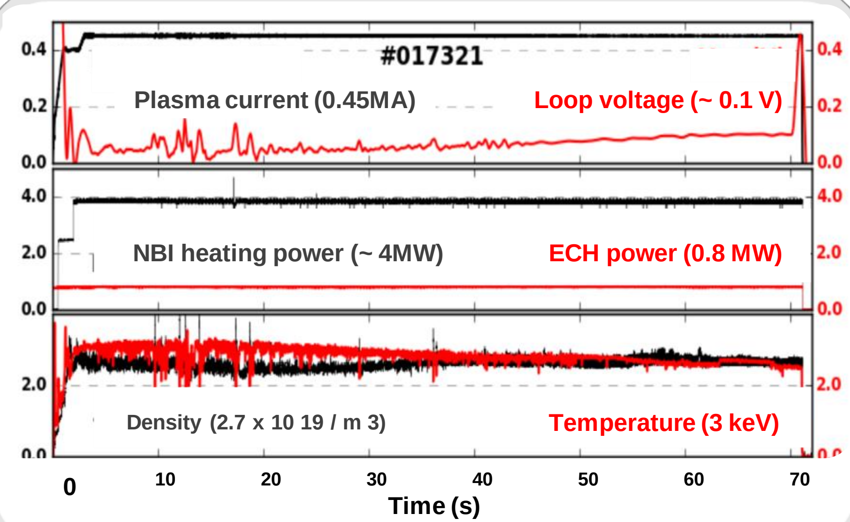
KSTAR는 지구 상에 무한에 가깝게 존재하는 수소를 원료로 사용하는 핵융합 발전 실험 장치이다. 수소를 1억도 이

국가핵융합연구소

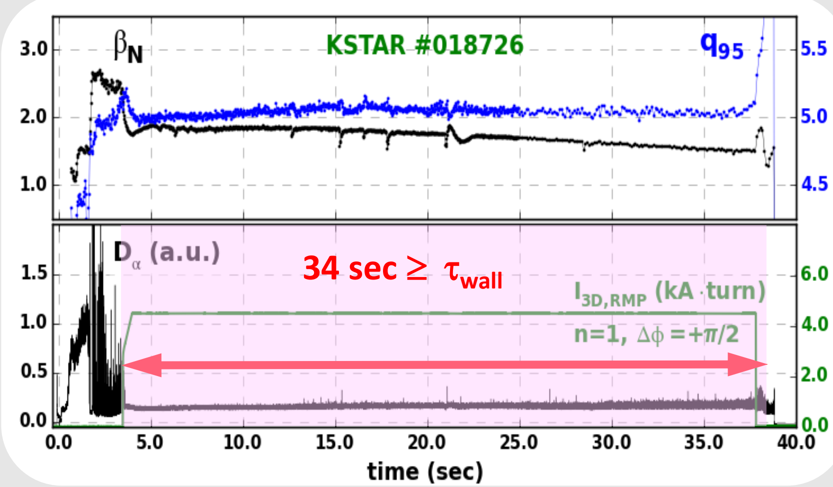
마를 유지할 수 있다"고 말했다.

김기만 국가핵융합연구소장은 "플라스마는 불안정하게 움직이는 특성이 있는데 소프트웨어로 전자기장을 미세하게 조절해 70초 정도 유지할 수 있으면 그 이상 시간을 늘리는 것은 어렵지 않다"면서 "내년부터는 핵융합로가 고온에서 오래 버틸 수 있는 소재나 안전 장치 연구도 본격적으로 시작할 계획"이라고 말했다.

- **ITER operation .. High-performance plasma longest operation (over 1 minute, '16)**
- **ITER challenge .. Edge-Localized Mode(ELM) suppression (the longest in the world, '17)**
- **Started research on operation mode for advanced fusion reactor ('16~)**
- **Re-analysis of plasma physical phenomena (advanced diagnostics device, simulation)**



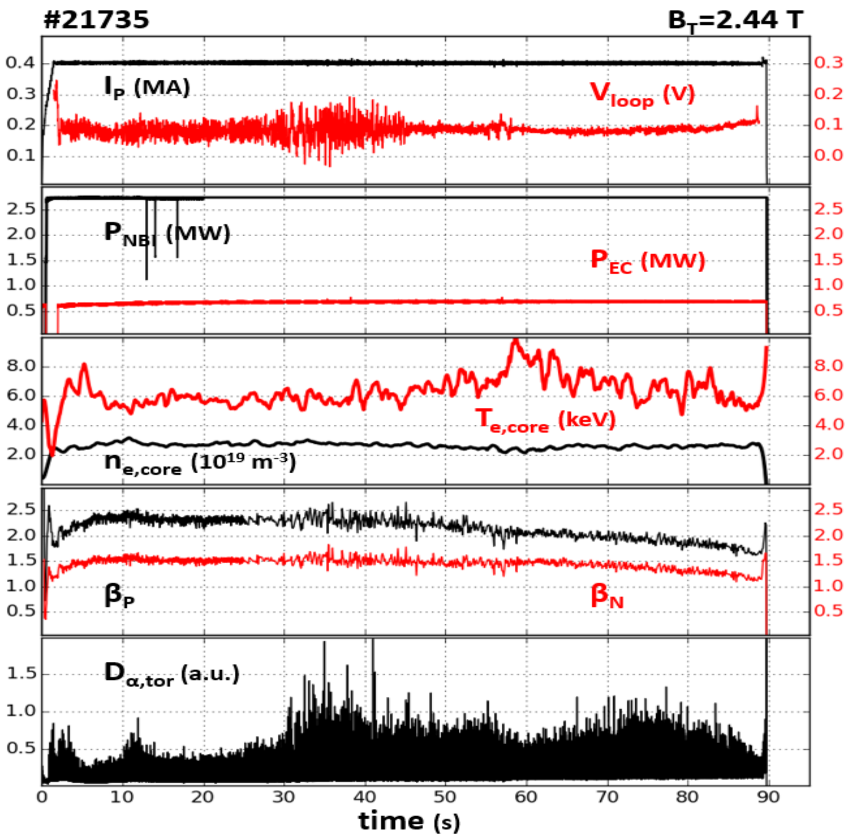
Obtained long-time maintenance technology of high-performance H mode (more than 1 minute)



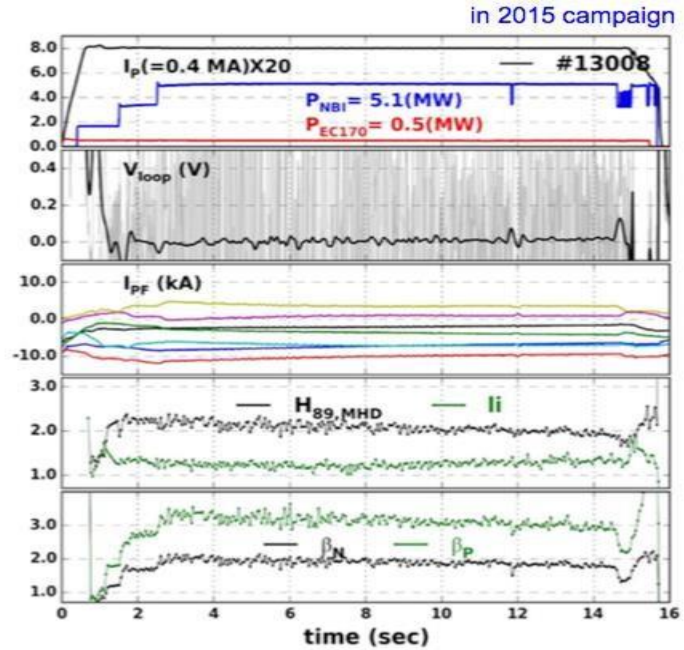
Achieved suppression of plasma ELM using in-vessel control coil (IVCC) (~ 34 sec)

Long-pulse sustainment of high performance discharge

- **In 2019, 90 s of H-mode operatio n achieved with NBI+ECH**



- **In 2015, fully non-inductive high β_P (>3) discharge was found**
  - NBI driven fully non-inductive
  - $\beta_P = 3.0$, $\beta_N = 2.0$,
  - Pulse limited due to PFC overheating by excessive fast ion loss



Fully inductive, high β_P(> 3.0) discharge at 3.0 T

Research and upgrade plan for higher beta and steady-state operation

2008 → **2017**

First plasma
(ECH 84 GHz)

Long-pulse H-mode
(NBI~5.5 MW)
(ECH~1 MW)

Long-pulse H-mode research

- *Long pulse H-mode (>70s)*
- *ELM research & control (>30s)*
- *Alternative operation modes (ITB, low q, ..)*

2017 → **2021**

Heating upgrade
(NBI~12 MW)
(ECH~6 MW)

Advanced scenario & MHD research

- *Stable high beta operation*
  (β_N>3.0, T_{ion} ~ 10 keV)
- *Advanced mode develop.*
  (hybrid, ITB, low q)
- *MHD & disruption control*

2021 → **2025 ~**

Divertor upgrade
(Tungsten divertor)
(Detached divertor)
(Diagnostics)

Advanced current drive
(LHCD~4 MW) or
(Helicon CD~4 MW)

Steady-state & reactor mode research

- *Tungsten divertor & active cooling (10 MW/m^2)*
- *Advanced current drive under test*
  (HFS LHCD & Helicon CD)
- *Steady-state operation (~300s)*

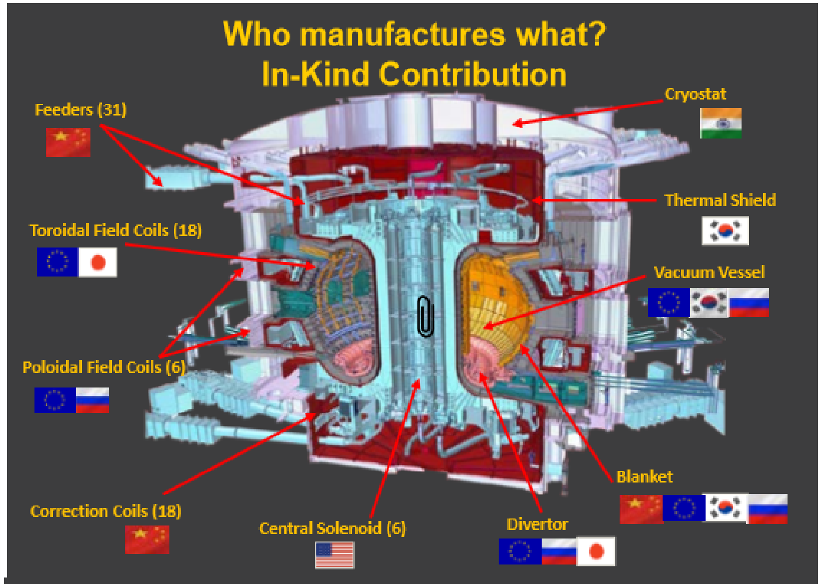
ITER (International Thermonuclear Experimental Reactor)

Project Goals

- **Final engineering demonstration for commercialization of fusion energy** through international joint construction and operation efforts
- Target of achieving 500MW thermal power and 10-fold energy amplification rate (Q)
- 7 countries: USA, EU, Japan, Russia (Apr. '88), China (Jan. '03), **Korea (Jun. '03),** India (Dec. '05)

ITER Project

- **ITER** is on the way to commercial **fusion reactor and it** will **demonstrate the feasibility and integration of science and technologies**, and **safety** features for a fusion reactor;
- The self-sustained D-T burning plasma in ITER will generate **500 MW** which is **10 times more power** than it receives;
- ITER enterprise will create a new **collaborative culture and standard solving energy and environmental problems** and contributing to the world peace;
- All of the **intellectual properties** obtained belongs equally to all seven Members.



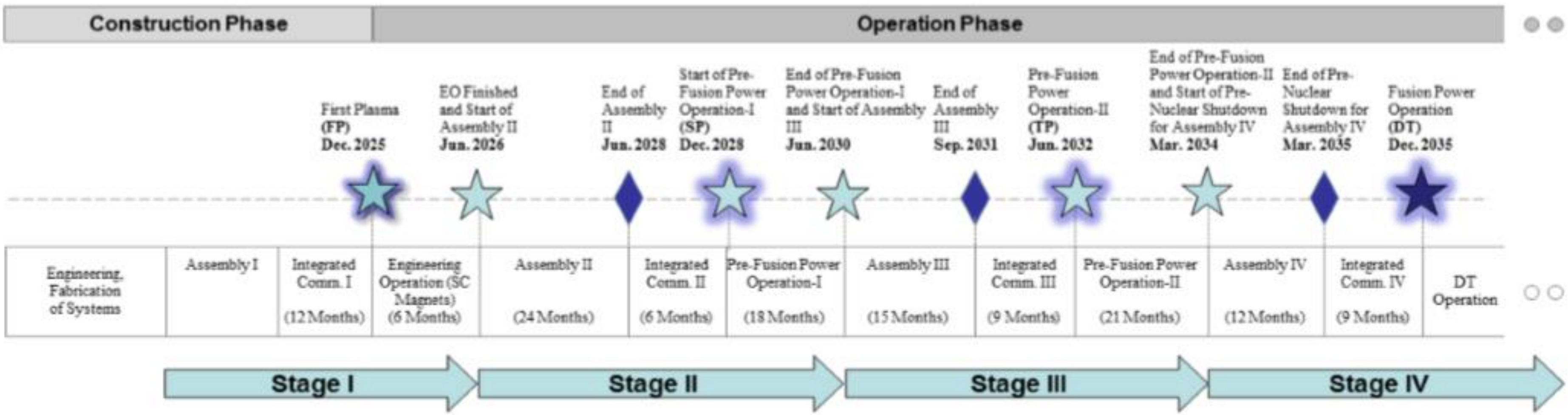
R=6.2 m, a=2.0 m, Ip=15 MA, BT=5.3 T, m=23,000 tons, (H) 29.0 m x (D) 28.6 m

◆ ITER Organization & Seven Domestic Agencies

- The 7 ITER Members make in-cash and in-kind contributions to the ITER Project. They have established Domestic Agencies.
- The ITER Organization manages the ITER Project in close collaboration with the 7 Domestic Agencies.
- 519 staffs working together 321 P, 198 G as of June 2014

ITER Research Plan (IRP) : Staged approach to DT operation

- Not all ITER systems available at same time → Staged Approach to DT operations and achievement of Project's goals
- Basic tokamak configuration ready for First Plasma → Progressive installation of Plasma Facing Components, In-vessel coil power supplies, fuelling and H&CD systems, Diagnostics, etc., up to DT operation



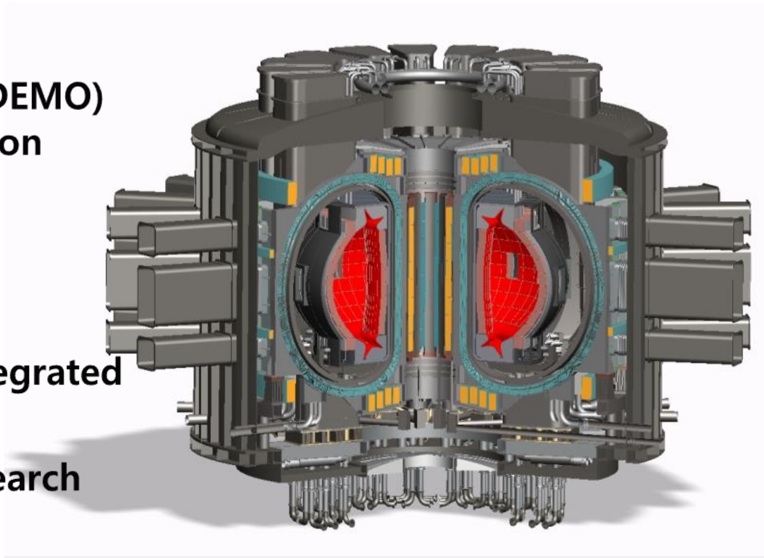
ITER Research Plan is publicly available as ITER Technical Report (ITR-18-003)

A. Loarte, ITER IO

K-DEMO - Goals and Strategy

Project goals

- **Design** Korean fusion demonstration reactor (K-DEMO)
- **Research base technology** for fusion demonstration reactor



Key research fields

- **Fusion reactor optimization research through integrated simulator**
- **Diverter/blanket design and core technology research**
  ※ Diverter: Component for heat and particle control in vacuum vessel
  ※ Blanket: Tritium fuel and thermal extraction component

Design strategy

- **Design of fusion reactor with economic feasibility**
  - ✓ Minimize device size (similar to ITER)
  - ✓ Maximize fusion containment performance (twice or more that of ITER)
- **Operation Phase 1: Materials testing**
  - ✓ Core plasma control technology, material testing
- **Operation Phase 2: Demonstration fusion power plant**
  - ✓ Fusion output (> 2 GW), power generation (net 0.4 GW level)
  - ✓ Self sufficiency of tritium fuel

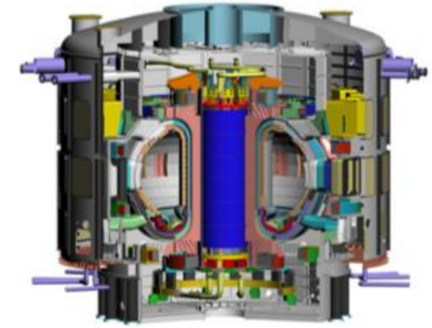
■ Main Parameters
- R = 6.8 m / a = 2.1 m
- B_0 = 7.0~7.4 T / B-peak = 16 T
- elongation = 1.8
- triangularity = 0.625
- Plasma current > 12 MA
- Te > 20 keV

■ Other Features
- Double-null & Single-null configuration
- Vertical Maintenance
- Total H&CD Power = 80~120 MW
- P-fusion = 2200~3000 MW
- P-net > 400 MWe at Stage II
- Number of Coils : 16 TF, 8 CS, 12 PF

KO Approach for K-DEMO Technology

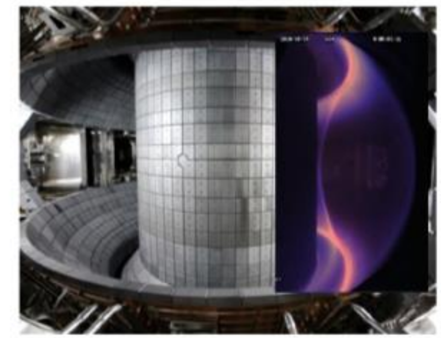
● Fusion Plant EPC Technology (Construction)

- Engineering design and manufacturing (Codes & Standards)
- License technology for fusion safety
- Experience on ITER Construction and License from French Authority



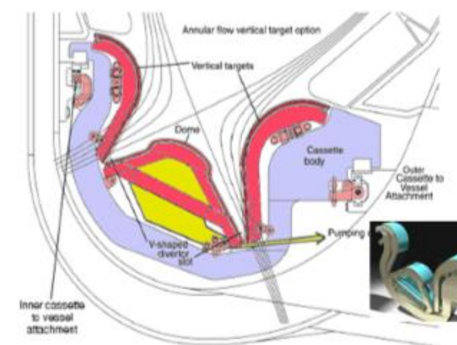
● Reactor Burning Plasma Technology (Steady-state Operation)

- High performance H-mode steady-state operation scenario
- High β_N (>4) and high pressure burning plasma
- Based on KSTAR advanced-mode experiment + ITER D-T operation



● Fusion Reactor Engineering (Breeding Blanket Technology)

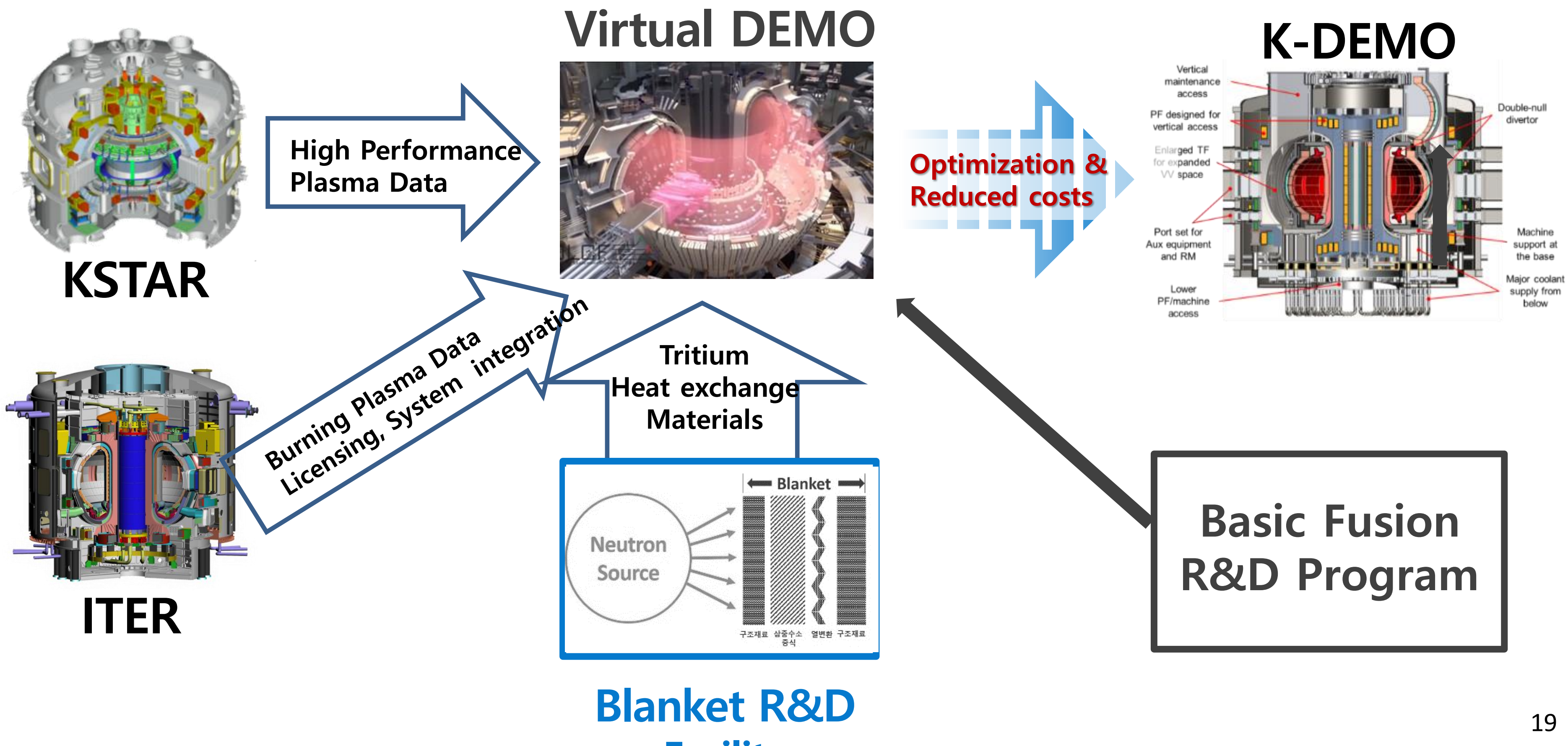
- RAFM structure and other fusion materials (Fusion Neutron Source)
- Tritium breeding technology (Fusion Neutron Source)
- High power exhaust and divertor technology
- ITER TBM + Fusion Engineering Facility



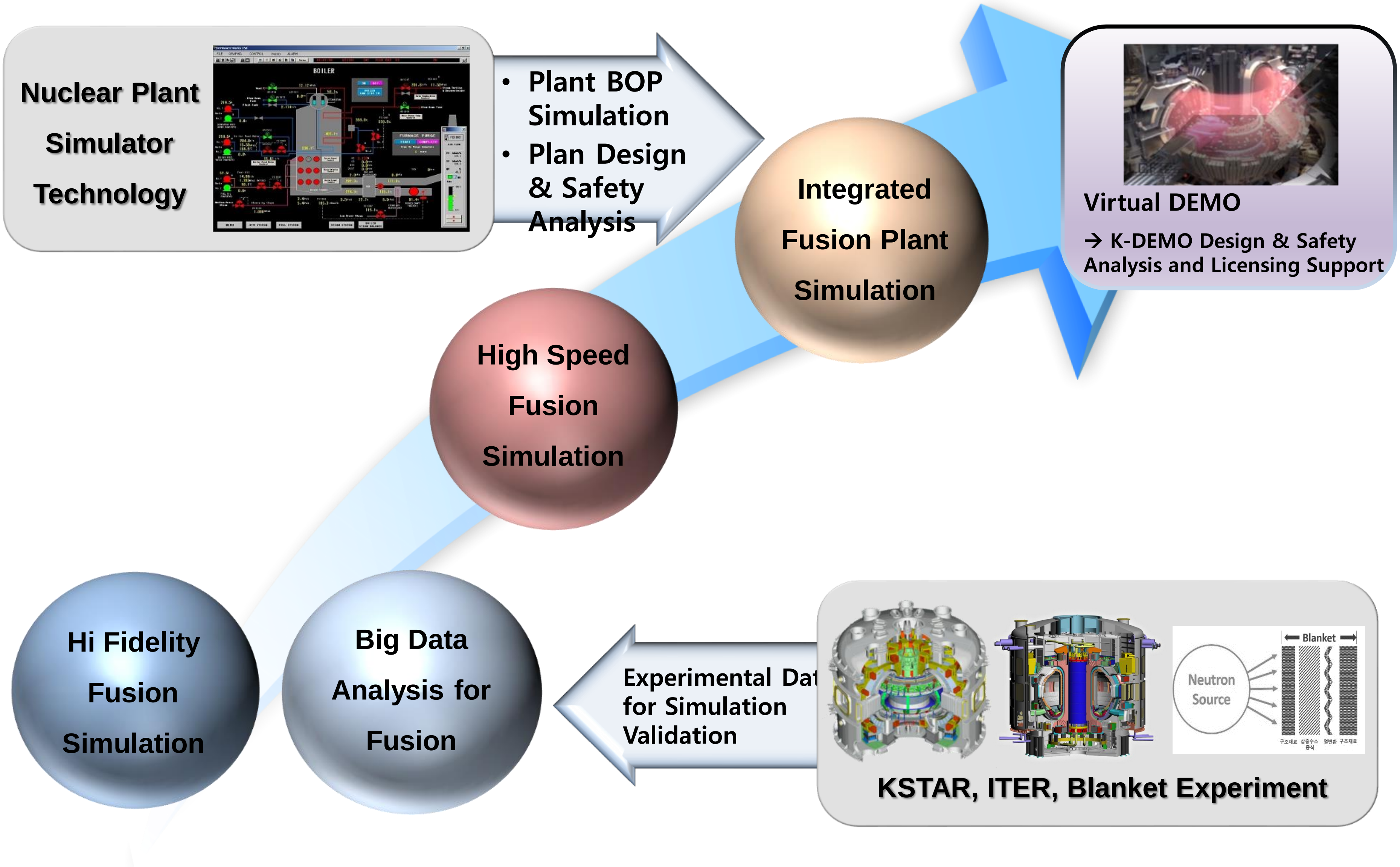
Divertor Development

Virtual DEMO – What is it?

- **Bridging the present (KSTAR, ITER) and the future (K-DEMO) reactors via Computer Simulation**
  - Validated simulations with data provided by KSTAR, ITER and Blanket facilities
  - Integrated simulations of engineering components (Blanket, BOP, licensing etc)
  - Optimization of K-DEMO simulations, Reduced risks and construction costs

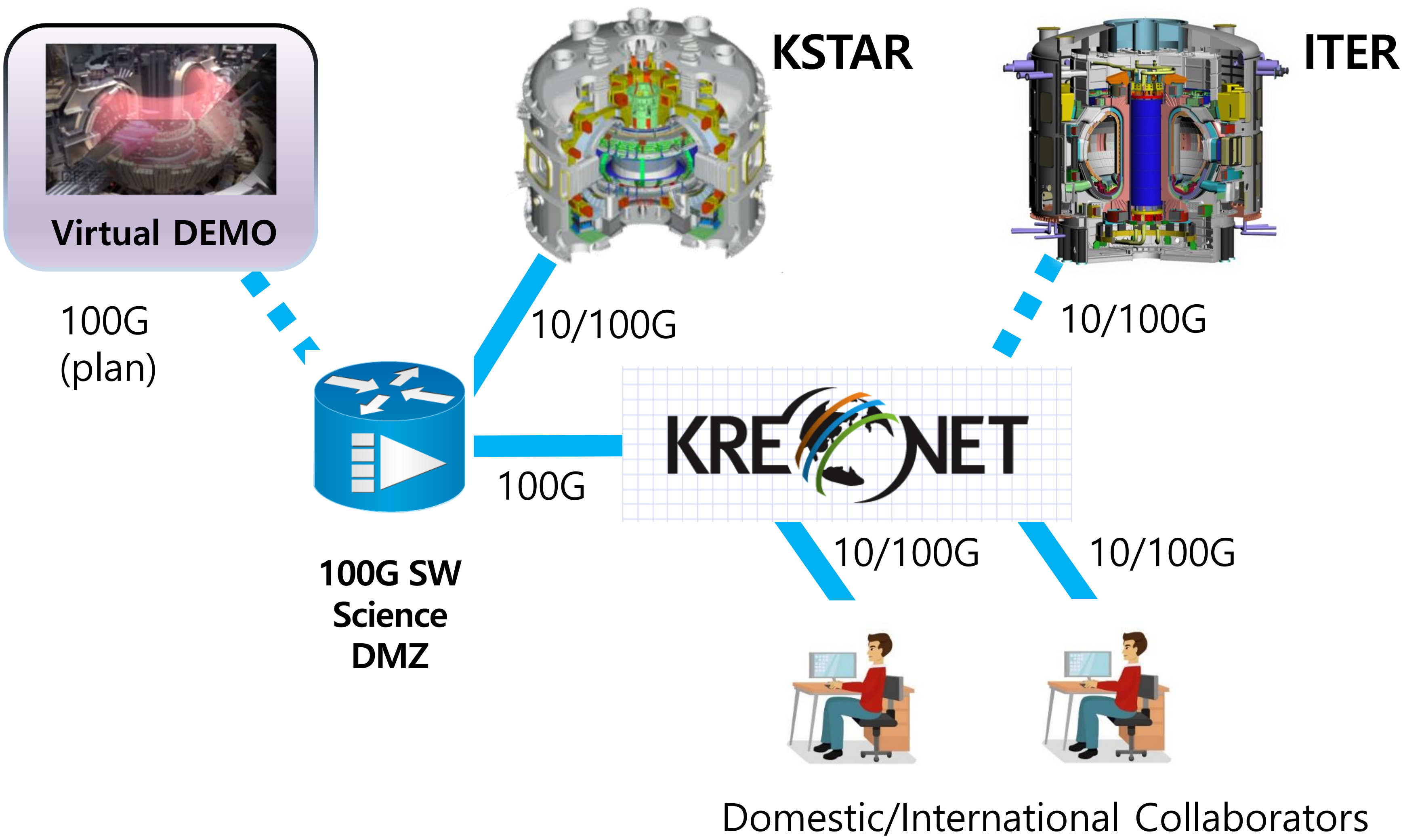


Virtual DEMO – How to realize it?

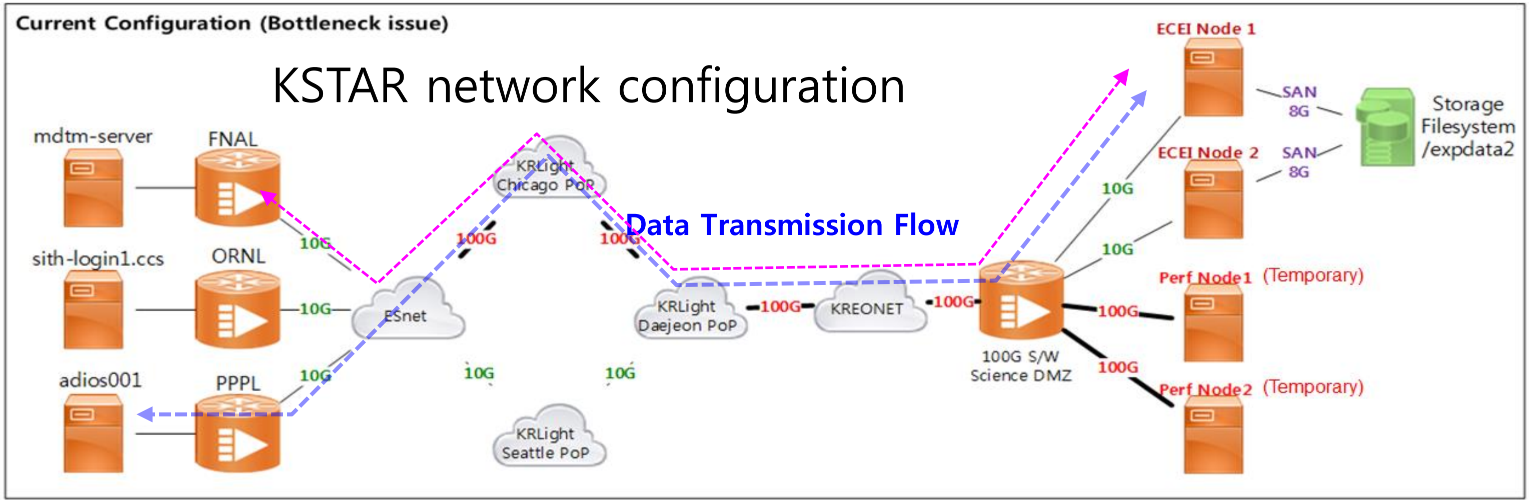


Virtual DEMO – High speed network is key!

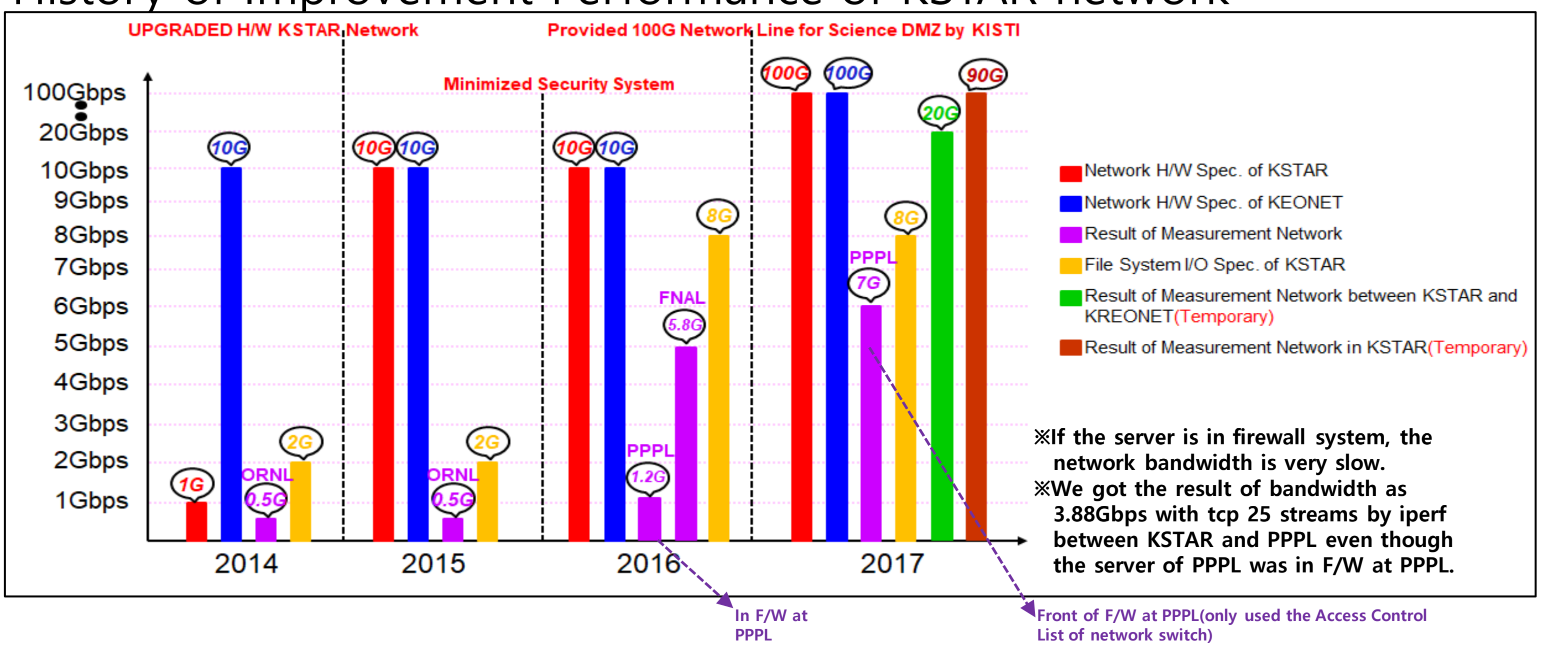
- **Currently using KREONET in close collaboration with KISTI for KSTAR data sharing**
- **Plan to include V-DEMO and ITER in future**



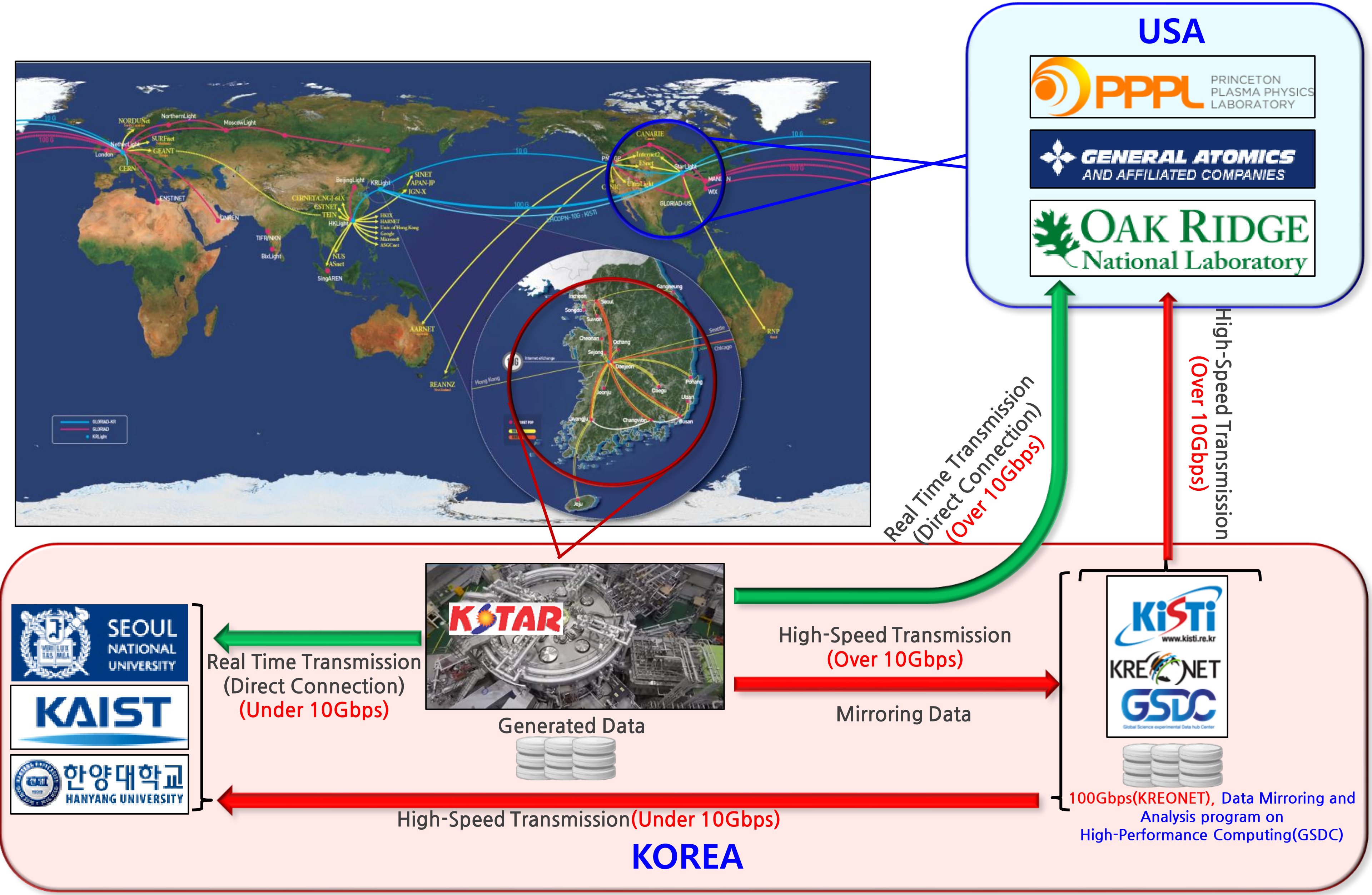
Testing the Fast Data Transmission between KSTAR and PPPL with KERONET



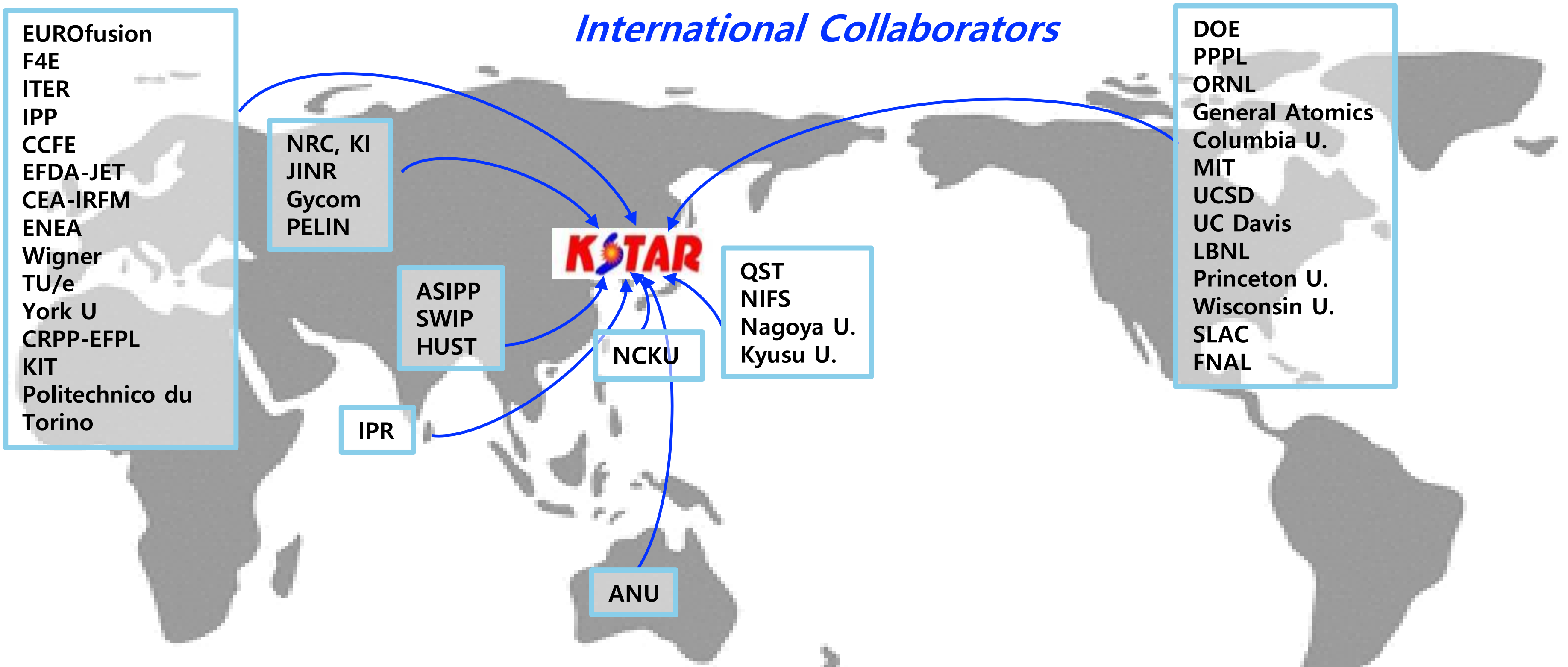
History of Improvement Performance of KSTAR network



Planning the fast data sharing architecture into the world



We appreciate the contribution and collaboration of the international partners in Korean fusion program



EU & Russia :

- Heating & CD (CEA)
- Diagnostics (ENEA, TU/e, Wigner)
- PWI, fueling (ITER, PELIN)
- Theory & analysis (York U)
- Experiments (JET, AUP, WEST)
- ELM, PSI, CODAC (ITER)
- ETC

Asia & Australia :

- Heating & CD (QST)
- Diagnostics (NIFS, QST, Nagoya U, Kyushu U. ASIPP, HUST, ANU)
- PWI, fueling (ASIPP, SWIP)
- MHD physics & simulation (NCKU)
- Joint workshop (A3 project)
- ETC

USA :

- Heating & CD (PPPL, GA, SLAC)
- Diagnostics (ORNL, MIT)
- 3D physics (GA, PPPL, Columbia U)
- Plasma control & CODAC (GA, PPPL, ORNL, FNAL)
- ETC

Thank you for your attention !

감사합니다